

**More Choices for Connecting Prefabricated Bridge Elements and  
Systems (PBES)**

**Quarterly Progress Report  
For the period ending August 31, 2019**

Submitted by:

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ACCELERATED BRIDGE CONSTRUCTION  
UNIVERSITY TRANSPORTATION CENTER

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## **1. PROJECT ABSTRACT**

Prefabricating bridge elements and systems (PBES) offers major time and cost savings, safety advantages, and can solve many constructability challenges as envisioned by the FHWA to revolutionize bridge construction in the US. Several types of PBES connections have been evolved in the last decade but many of these connections use Ultra-High performance concrete (UHPC). UHPC has superior mechanical properties but is very expensive and requires special expertise to work with it. Moreover, robust UHPC mixes are currently proprietary which sometimes limits DOTs that are trying to avoid sole-sourcing and bidding issues from using UHPC. Therefore, finding other alternatives and choices for PBES connections can be extremely beneficial. The goal of this project is to identify and proof-test potential alternatives to replace UHPC in PBES and ABC seismic and non-seismic connections. An experimental approach that consists of material and large-scale structural tests at UNR laboratories will be considered. The specific research objectives of this study are: (1) collect and select potential alternative materials (e.g. advanced grouts or polymer concrete) to replace UHPC in PBES connections; (2) characterize the material and mechanical properties of selected alternatives; (3) conduct large-scale testing to study the response of the alternative materials as used in structural ABC applications. One tentative application that focuses on deck panels' connections will be considered.

## **2. RESEARCH PLAN**

### **2.1. STATEMENT OF PROBLEM**

Prefabricating bridge elements and systems (PBES) offers major time savings, cost savings, safety advantages, and convenience for travelers. According to the FHWA, the use of PBES is also solving many constructability challenges while revolutionizing bridge construction in the US. In the past decade, innovative PBES connections have been evolved and many of these connections used Ultra-High performance concrete (UHPC). UHPC has superior mechanical properties and durability. However, some of the limitations associated with UHPC wide spread use include: the very expensive price tag, the expertise needed to work with UHPC, it is labor intensive, and most of the robust mixes are currently proprietary. Several DOTs see the proprietary nature of UHPC leads sometimes to sole-sourcing and in turn, bidding issues. Thus, there is a growing interest nowadays to find other alternatives and choices for PBES connections. The goal of this project is to identify potential alternatives to replace UHPC in PBES and ABC seismic and non-seismic connections. These alternatives can include special or advanced grout, polymer concrete, fiber concrete, etc. One selected material or alternative will be tested for at least two different PBES or ABC connection types.

### **2.2. RESEARCH APPROACH AND OBJECTIVES**

Our approach for this proposed study is mainly an experimental approach that spans different types of material and large-scale structural tests at UNR laboratories. Two types of PBES connections that have traditionally used UHPC will be considered in this study to investigate and validate their structural response when new alternatives are used instead of UHPC. Note that benchmark response from conventional cast in place (CIP) construction or from research studies that tested such connections with UHPC will be used for new materials validation in this study. The first connection type is the most common ABC application that uses UHPC and can get more popular if other feasible options other than UHPC become available. This is the field joints used to connect

precast deck slabs as shown in Figure 1. Precast slab panels can be conveniently connected to prestressed concrete or steel girders using shear studs (Shrestha et al. 2017). Then, advanced materials such as UHPC are used to connect the precast deck panels while maintaining acceptable load transfer mechanism (e.g. slab reinforcement lap splices).

The specific research objectives of this study are: (1) collect and select potential alternative materials (e.g. polymer concrete) to replace UHPC in PBES connections; (2) characterize the material and mechanical properties of selected alternatives; (3) conduct large-scale testing to study the response of the alternative materials as used in structural ABC applications. The main application to test the alternative material is deck panels' connections.



**Fig. 1** – Field connections/joints for precast deck slabs (photo credit: Georgia DOT)

### **2.2.1. SUMMARY OF PROJECT ACTIVITIES**

An experimental approach will be used and several research activities will be executed to accomplish the objectives of this study. A summary of the proposed research tasks is as follows:

- Task 1 – Literature search and selection of UHPC alternatives for ABC connections
- Task 2 – Material and mechanical characterization tests
- Task 3 – Development of experimental program and specimens design
- Task 4 – Experimental testing of deck slabs joints
- Task 5 – Summarize the results in a final report

### **2.2.2. DETAILED WORK PLAN**

A detailed description of the proposed research tasks is presented in this section.

#### **Task 1 – Literature search on and selection of non-proprietary UHPC and other cementitious alternatives for use in ABC joints:**

A detailed literature search was conducted to determine possible and potential alternatives to replace UHPC for PBES connections. The literature search was divided into two main parts; (1) searching for alternative materials to replace UHPC in PBES Connections, (2) reviewing the previous experimental studies that were performed in PBES Connections.

**- Alternative materials to replace UHPC in PBES**

The main aim of this part of the literature is to select an alternative material to replace the UHPC in the PBES connections. Different materials have been searched as potential alternatives such as non-proprietary high performance and ultra-high performance fiber concrete, advanced grouts, ECC, and polymer concrete. After reviewing the mechanical properties of the materials, one type of polymer concrete (PC) named “T-17” seems to be promising. The selection of this closure material was based on some main aspects such as; it should provide simplified reinforcement configurations through the joints, provide smaller joints, provide better joint interface bonding and better long-term durability. Consequently, the closure material should satisfy the following mechanical properties; it should have good bond strength which can provide less rebar development length, less lap splice length and good bond to the existing precast concrete, it should have good flowability and less setting time, it should also provide high early strength and good durability properties.

The “T-17” polymer concrete has the good potential to replace the UHPC in the PBES connections. It was used before in many airports as a fast permanent repair to runways and taxiways because it can be cured to full hardness in less than 45 minutes.

The “T-17” polymer concrete has good features and advantages: wide application temperature range (14-100° F), fast setting (45 minutes at 70° F), high early strength (compressive strength of 2,500 psi @2hrs and 8,000-9,000 psi @24hrs), strong chemical bond, freeze-thaw resistant and high tensile strength (1.2 ksi). Table (1) shows some of the mechanical properties of the “T-17” polymer concrete.

**Table 1 – mechanical properties of “T-17” polymer concrete.**

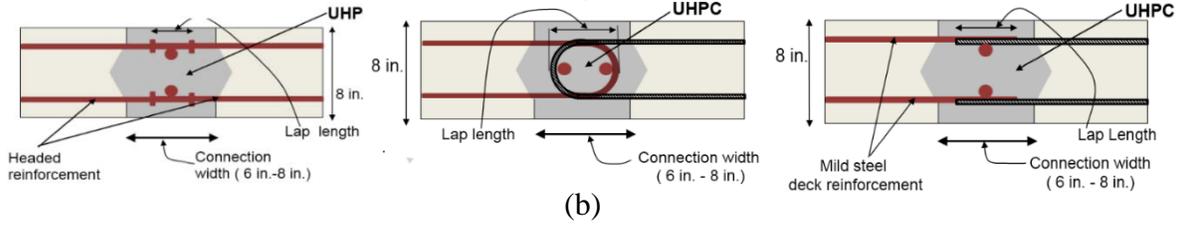
<b>T-17 Mortar (No Extension)</b>			
Compressive Strength	8000 – 9000 psi	(55 – 62 MPa)	ASTM C579 Method B
Flexural Strength	1800 – 2500 psi	(13-17 MPa)	ASTM D790
Linear Shrinkage	<0.2%		DuPont
Tensile Strength	1000 – 1200 psi	(6.90-8.25 MPa)	ASTM D638 Type I
Compressive Modulus	1.1-1.2 x 10 <sup>6</sup>	(7.50-8.50 GPa)	ASTM C579 Method B
Tensile Adhesion (pull-off concrete)	>250 psi	(>1.7 MPa)	ACI 503R

**- Previous experimental studies**

A large number of research works was conducted on the field of PBES connections. Some of them focused into trying different materials in the PBES connections and investigate the overall performance to select the most proper closure material, while the others investigated several parameters in the PBES connections such as; the type of field connections, joint configuration, details of reinforcement and different loading schemes.

Our scope in this part of the study is to review and report the previous experimental and numerical studies in the precast bridge deck field joints. Through the last decade, many researches started working on using a willing material in the PBES connections named “UHPC” like the work done by Ben Graybeal (2010). While all the research before this period was directed into investigating the behavior of the PBES connections with using different materials such as advanced grouts, high performance concrete (HPC) and HPC with fiber reinforcement.

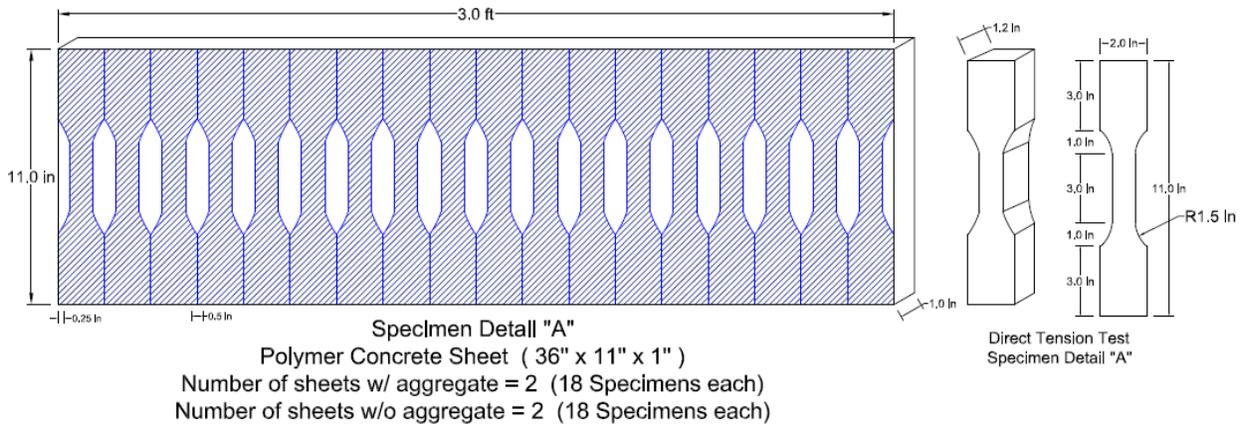




**Fig. 3** – Precast bridge deck field connections: (a) different joint configurations (female-female shear keys), (b) details of reinforcement (headed rebar, loop splice, and straight splice).

**Task 2 – Mechanical characterization of the selected UHPC-alternative material**

Most of the new or evolving cementitious materials are extensively tested to characterize fresh and harden state properties with less focus on mechanical properties characterization. In this task, the mechanical properties of the selected materials from Task 1 will be further characterized. Various material tests will be considered to determine compressive strength, tensile strength, Young’s modulus, and modulus of rupture from bending tests. Direct tension tests will be considered to better characterize tensile strength rather than using cylinders splitting tests or three- and four-point bending tests. Polymer concrete sheets were received and tension specimens will be prepared using water jet cutting. Figure 4 shows the cutting layout of the dog bone specimens and individual specimen’s dimensions.

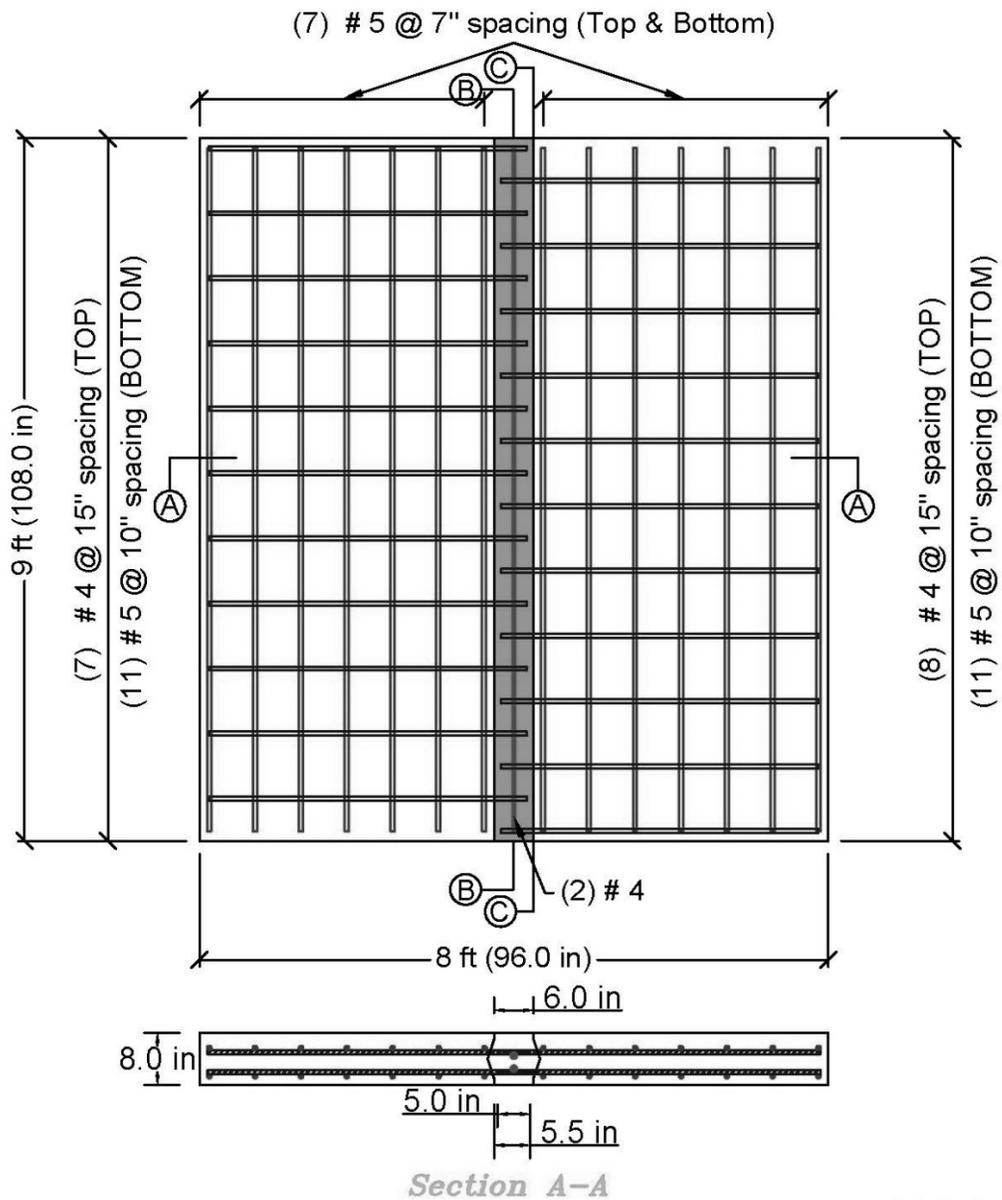


**Fig. 4** – Polymer Concrete specimens’ layout and dimensions for direct tension test

**Task 3 – Development of experimental program and specimens design**

The objective of this task is to work with the ABC-UTC and the project advisory panel to finalize the types of PBES and ABC connections, types of tests, and a number of specimens to consider using the alternative selected and tested materials from Tasks 1 and 2. Two types of connections and tests were proposed which are: (1) longitudinal connections of deck bulb tee girders that will be tested for flexure; (2) deck panels’ transverse connections that will be tested for flexure. Figures 5 and 6 show the details of reinforcement of the transverse and longitudinal specimens respectively. Five specimens were constructed to conduct three transverse and two longitudinal joints tests. Specimens of similar layout and design as what has been tested by FHWA for UHPC deck panel joints is replicated for comparisons. The details of the tested specimens are reported in

Table 2. The design of the specimens was done according to the AASHTO LRFD Bridge Design Specification (AASHTO, 2012). The positive and negative design moments were determined based on the AASHTO Equivalent strip method. The moment values provided in this method takes into account the largest values that could be experienced by the deck slabs with respect to different loading conditions. The bridge example that was used to analyze the reinforced concrete deck slab in this study has a cross-section consisted of five steel girders spaced at 12 ft on center and a deck slab of 8 in thickness.



**Fig. 5** – Structural details for the transverse specimens.

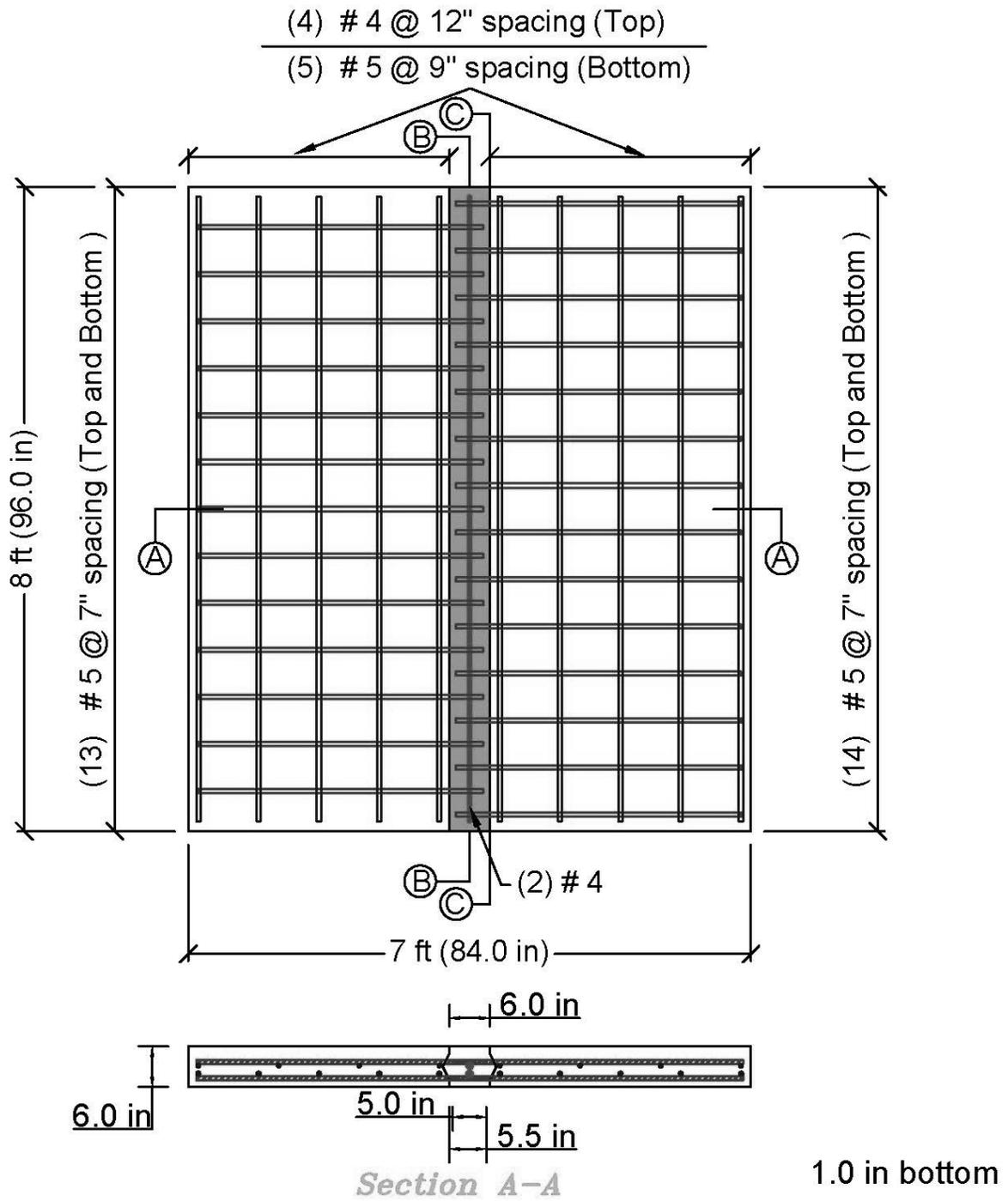


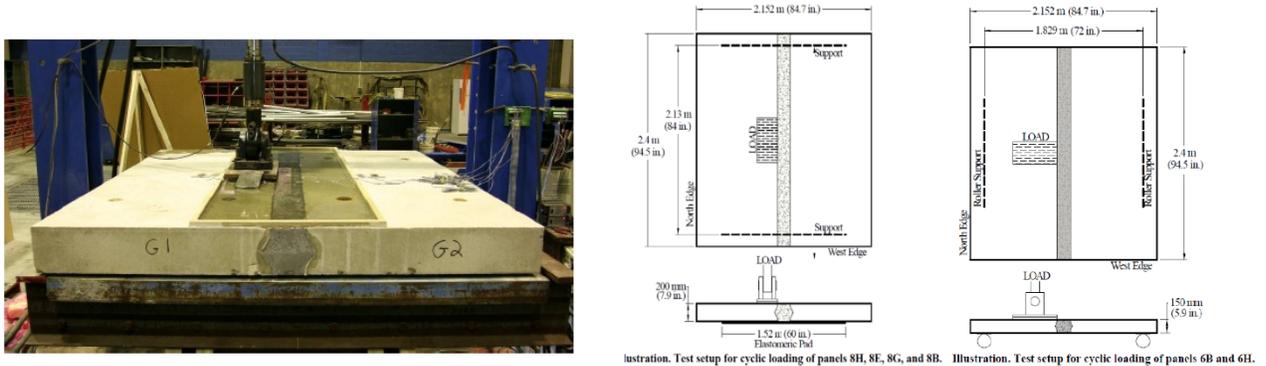
Fig. 6 – Structural details for the longitudinal specimens.

**Table 2 – Test Specimens**

Specimen Name	Joint orientation	Overall specimen dimensions	Closure material	Lap splice type	Joint width	Lap splice length
SP-T-S-UHPC	Transverse	9'x 8' x 8''	UHPC	Straight	6''	5''
SP-T-S-PMMA	Transverse	9'x 8' x 8''	PMMA	Straight	6''	5''
SP-T-U-PMMA	Transverse	9'x 8' x 8''	PMMA	U-bar	6''	4.5''
SP-L-S-UHPC	Longitudinal	8'x 7' x 6''	UHPC	Straight	6''	5''
SP-L-S-PMMA	Longitudinal	8'x 7' x 6''	PMMA	Straight	6''	5''

**Task 4 – Conduct experimental testing of precast deck slabs with new joint connection**

Extensive precast deck panels with field and UHPC joints have been tested (e.g. Perry and Royce 2010, Graybeal 2010, Hartwell 2011). Testing procedures from previous studies is adopted to conduct large-scale testing on deck panels connected using the new alternative material. The FHWA test setup and specimens dimensions (Figure 7) will be almost replicated for comparison purposes with UHPC (Gaybeal 2010). The construction and assembly of all the deck panels for the test specimens have been completed at UNR as shown in Figures 8-13. The figures show also the sequence of construction. Recently, we have finished experimental testing of the transverse and the longitudinal specimens.



**Fig. 7 – FHWA cyclic test setup for deck panels with UHPC joints (Graybeal 2010)**



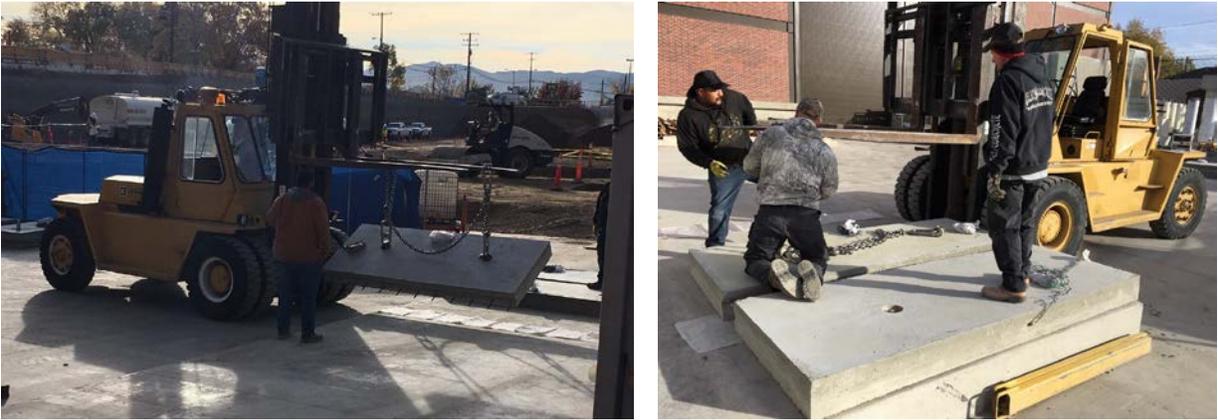
**Fig. 8** – Formwork for construction of deck panels and specimens



**Fig. 9** – Deck panels' construction, reinforcement, and cast concrete



**Fig. 10** – Close-up views of the constructed deck panels and shear keys for the field joints



**Fig. 11** – Alignment and assembly of test specimens at UNR



**Fig. 12** – UHPC and polymer concrete Closure pours for the field joint for the test specimens



**Fig. 13 – Deck panels test setup at UNR**

## 4.1 – Test Results

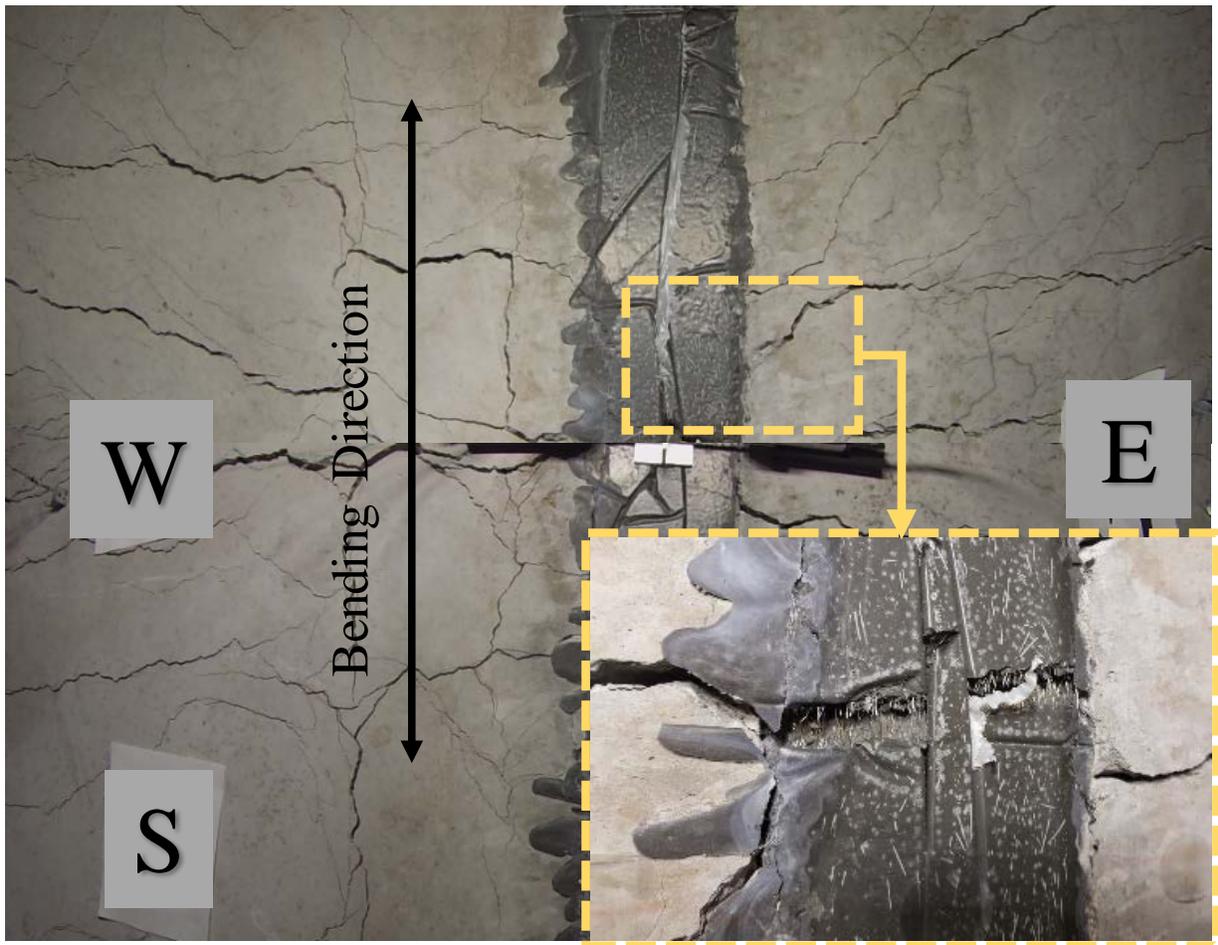
All the test results were processed and analyzed to study the performance of the UHPC and PMMA-PC field connections. The summary of results of the tested specimens was reported in Table 3.

**Table 3 – Summary of Test Results**

<b>Specimen name</b>	<b>Ultimate load (kips)</b>	<b>Ultimate mid-span displacement (inches)</b>	<b>Initial stiffness (kips/in)</b>
<b>SP1-Transverse-Straight splice-UHPC</b>	117.9	2.33	240
<b>SP2-Transverse-Straight splice-PC</b>	113.2	2.53	165
<b>SP3-Transverse-Loop splice-PC</b>	122.55	2.63	215
<b>SP4-Longitudinal-Straight splice-UHPC</b>	115.85	1.51	240
<b>SP5-Longitudinal-Straight splice-PC</b>	98.25	1.41	200

### 4.1.1 – Test Results of Specimen “SP1-T-S-UHPC”

The measured peak load of specimen “SP1-T-S-UHPC” was 117.9 kips at 2.33 in mid-span vertical displacement. The observed mode of failure for the UHPC transverse specimen was yielding in the main reinforcement due to flexure accompanied with crushing of the concrete at the top part of the loaded west side of the specimen. Deep and wide flexural cracks were observed at the bottom face of the precast slabs interrupted by two main localized cracks in the UHPC at the measured peak load. An interface crack at the top surface of the slab was observed between the unloaded east side and the UHPC connection at the peak load as shown in Figure 14. The depth and length of this interface de-bonding were then increased as the applied displacements increased. After reaching the peak load, a series of drops in the force capacity was observed along with excessive flexural cracking at the bottom and crushing of the deck panels’ concrete at the top (see Figure 14). The test was stopped after a rebar popping sound was heard after reaching approximately 80% of the peak load, which was found to indicate the rupture of the bottom transverse rebar inside the field connection. The flexural capacity of the specimen was much bigger than the required limit state moments (Ultimate and Service) specified in the AASHTO LRFD using Equivalent strip method. Therefore, the proposed UHPC field connection was capable of creating a precast deck system that can emulate the behavior of the cast-in-place deck systems in terms of strength requirements.



**Fig. 14** – Crack pattern, damage, and mode of failure at the top and bottom sides of specimen SP1-T-S-UHPC.

#### 4.1.2 – Test Results of Specimen “SP2-T-S-PC”

The measured peak load of specimen “SP2-T-S-PC” was 113.2 kips at 2.53 in mid-span vertical displacement. The observed mode of failure for the PC transverse specimen was similar in the beginning to the UHPC case with yielding in the main reinforcement due to flexure. However, a rebar rupture was observed at the peak load of the specimen which caused a sudden drop in the ultimate load capacity of the specimen. Crushing of the concrete was then observed at the top surface of the loaded west side of the specimen and continued to propagate through the joint until reaching the unloaded east side. Deep and wide flexural cracks were observed at the bottom face of the precast slabs, these cracks continued to propagate through the joint when approaching the peak load. No interface cracking was observed at the top surface of the slab between the precast slab and the PMMA-PC connection at the peak load. However, a short-length and small-depth interface cracking of approximately 0.2 in was observed at the top surface of the slab between the unloaded part and the PC connection while approaching the end of the test. The test was again stopped after reaching approximately 80% of the ultimate load. Figure 15 shows the overall damage and final status of the SP2-T-S-PC specimen after testing.

The overall load versus the mid-span vertical displacement obtained from three different string potentiometers for the first and second specimens are presented in Figure 16. It is noted that the data acquisition readings in the third cycle of SP2-T-S-PC test had some noise that partially affected the quality of the load-deflection relationships at this loading level. Two main observations can be drawn from Figure 16: (1) the overall behavior of the two specimens with UHPC and PC joints is very comparable, and (2) the flexural capacity of both specimens exceeded the two code limit states, i.e. service and ultimate loads specified in the AASHTO LRFD using Equivalent strip method. Therefore, both UHPC and PC field connections were capable of providing an ABC precast deck system that can emulate the behavior of conventional CIP deck systems in terms of strength requirements.



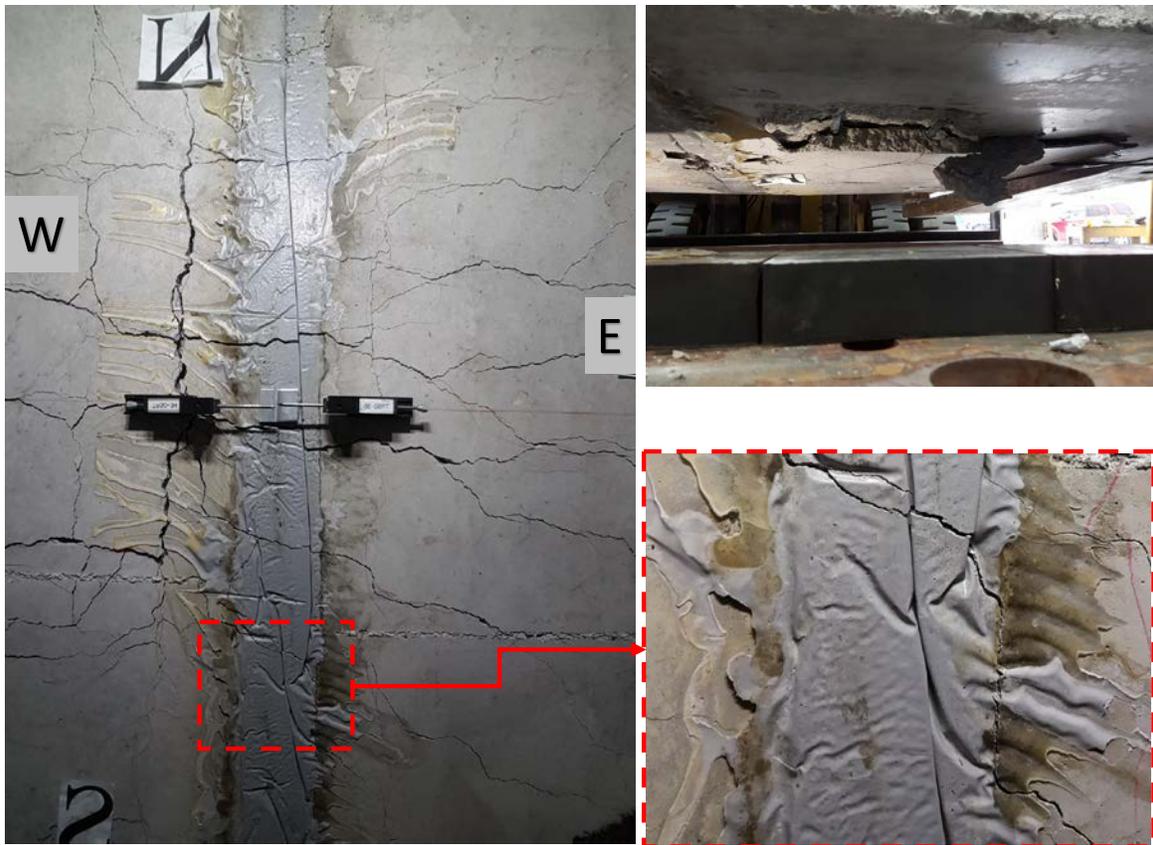


Fig. 15 – Crack pattern, damage, and mode of failure at the top and bottom sides of specimen SP2-T-S-PC.

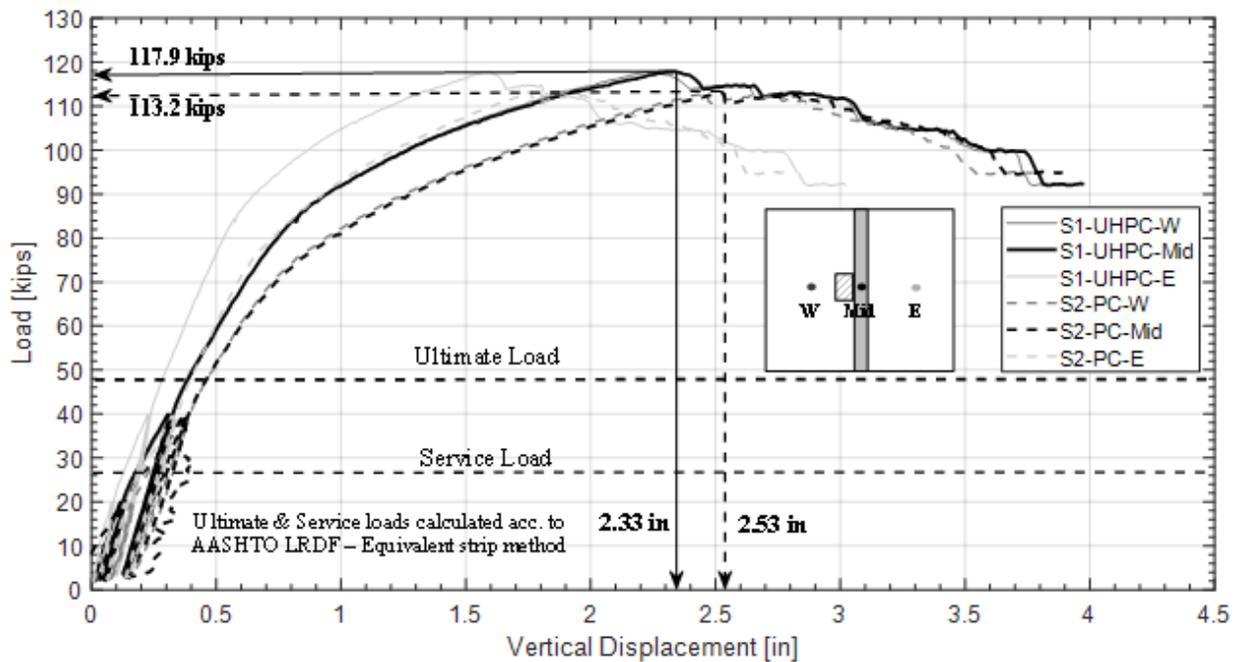


Fig. 16 – Load-deflection relationship at mid-span of specimens S1-UHPC and S2-PC as measured at three different locations.

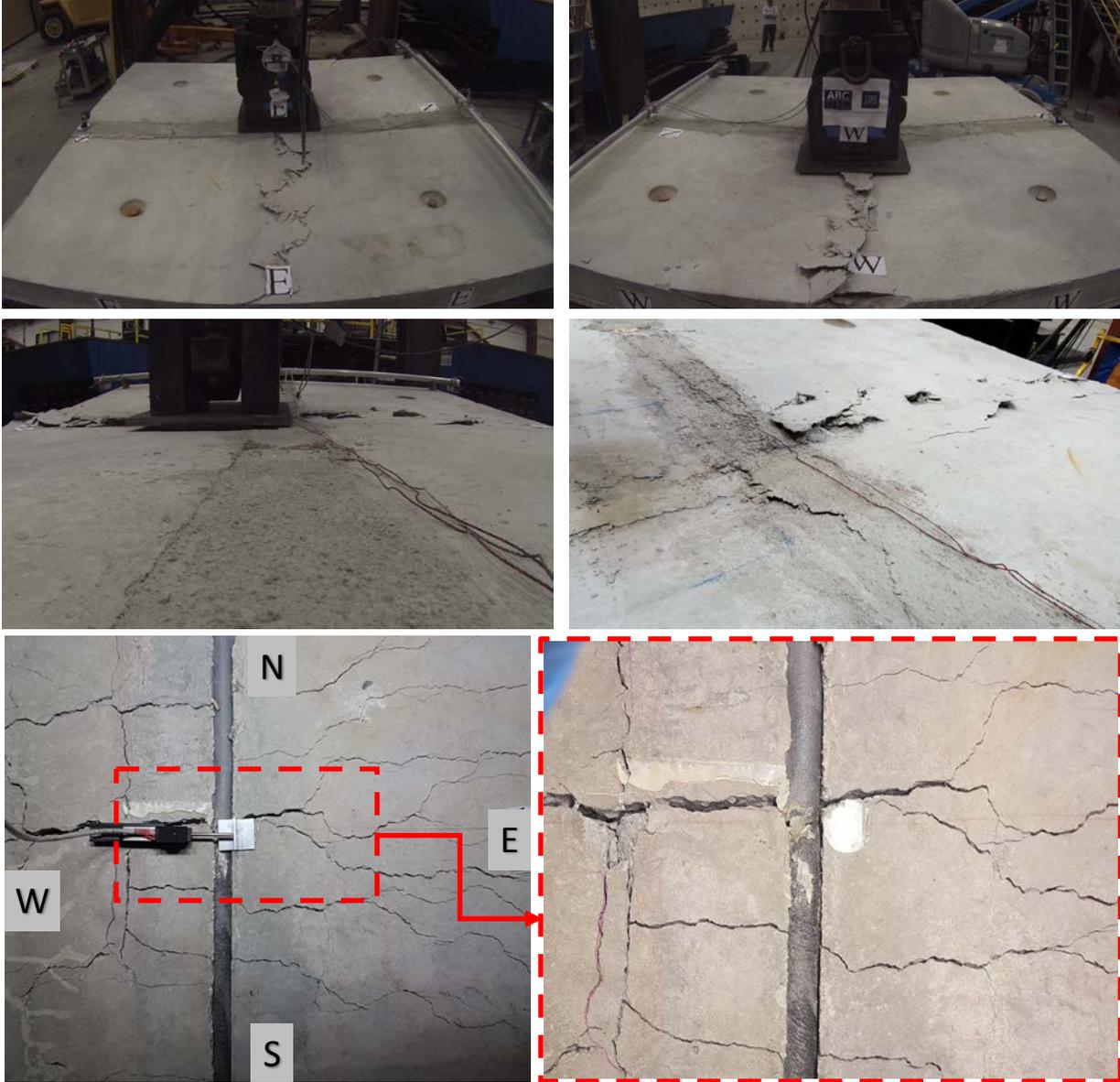
The load-deflection curves shown in Figure 16 can be divided into different regions of behavior. The first portion of the behavior represents the elastic behavior of the specimen when the applied load is approximately below 20 kips. During this stage, only hair flexural cracks in the longitudinal direction were observed in the bottom face of the slab. A hair transverse crack located approximately 5 inches apart from the edge of the connection and ran parallel to the connection in the loaded west side of the slab was also observed. No cracks were observed in the unloaded east side of the slab. No interface de-bonding or concrete crushing was observed during the “service” level loading of the behavior. No cracks were also observed in the field joints because of the higher tensile strength of the UHPC and PC as compared to the conventional concrete. The second region in defining the load-deflection curve represents the onset and progression of the inelastic behavior as the applied load exceeded the elastic load. This started in the third and fourth cycles of loading around the 40 kips vertical load when the flexural stiffness decreased and the residual displacement increased. The cracks at this level were still narrow and the main reinforcement was not yet yielded. It is worth noting that there were no flexural or interface cracks observed in the field connections until reaching the AASHTO specified ultimate load. The slight inelastic response continued as the load increased to approximately 85 kips and 75 kips for specimens S1-UHPC and S2-PC, respectively. As the load increased beyond this limit, the third region of the load-deflection curve can be defined by the significant reduction in stiffness as the specimens started to soften due to yielding of the middle and west side transverse reinforcement in the bottom mesh. Hence, deep and wide flexural cracks were observed in the bottom side of the slab. No rebar slip was observed until reaching the peak load for both specimens. Following the peak load capacity, the fourth region can be defined by a global softening behavior where the load capacity started to decrease with larger displacements. It is noted that the goal of pushing the specimens to such high levels of loads and displacements beyond code-required limits was to have better understanding of mode of failure and check whether the different system components stay intact.

It can be also seen from Figure 16 that the UHPC specimen exhibited larger flexural stiffness than the PC specimen because of the higher tensile and compressive strengths of UHPC. The early measured flexural stiffness of the UHPC specimen was found to be 240 kips/in versus 190 kips/in for the PC specimen, i.e. the PC specimen stiffness was about 80% of that of the UHPC specimen. To further investigate the relative deflection between two slab panels in a given specimen, the deflection was observed at three different locations in the middle of the specimen as illustrated in Figure 16. It is shown that the loaded west side of the slab and the field joint deflection were almost identical which was the case for both specimens. However the unloaded east side attained lower deflections, which was expected because of the asymmetry of the specimen loading in the longitudinal direction, i.e. east-west direction. Another interpretation for this observation is that the field connection is not transferring the full applied loads between the two sides of the slab as there was discontinuity in the reinforcement between both the two sides. Moreover, this difference in deflections increased with the increase of the applied load due to the influence of the reduction in stiffness of the slabs after the propagation of excessive cracking. This is consistent with results from a previous finite element study (NCHRP 10-71, 2011) which showed that the shear and moment forces on the field joint are greatly reduced due to the stiffness reduction accompanied with cracking of the specimen.

#### **4.1.3 – Test Results of Specimen “SP3-T-L-PC”**

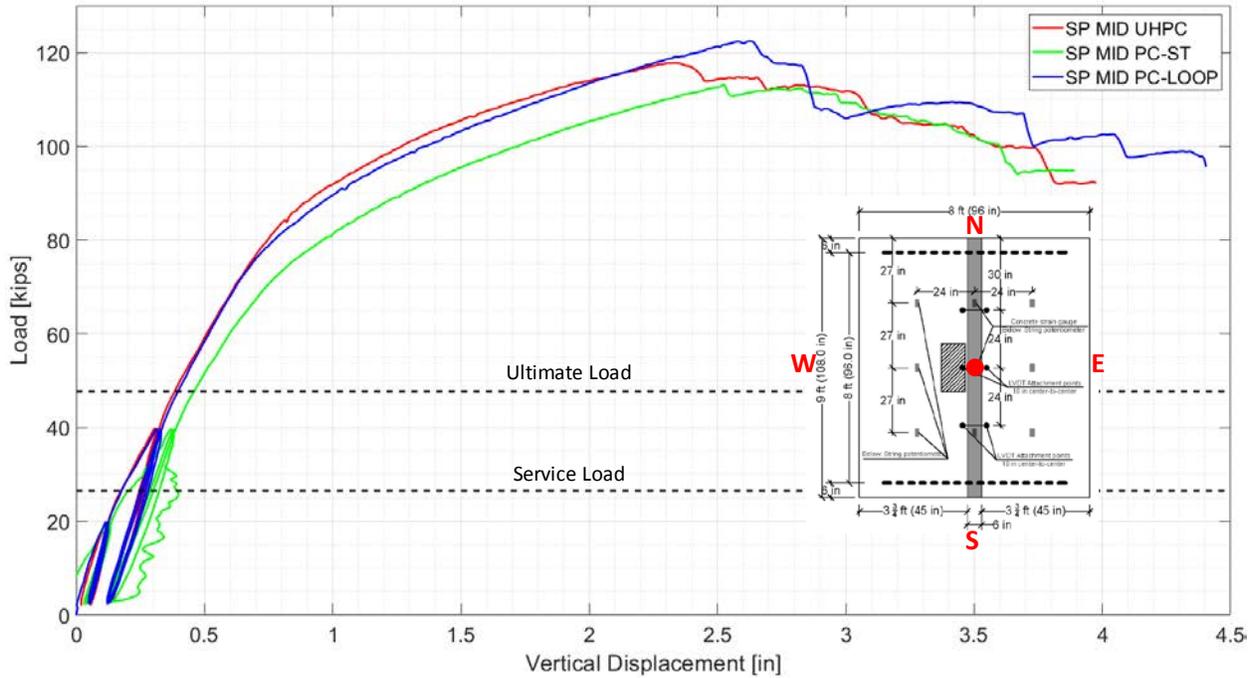
The observed mode of failure for the PMMA-PC transverse specimen with loop splice was yielding in the main reinforcement due to flexure accompanied with crushing of the concrete at

the top part of the slab towards the loaded side of the specimen. After reaching the maximum load there was crushing of concrete in the west side of the slab. Afterwards, crushing started to propagate across the span in the east and west sides includes significant crushing damage observed in the west side. Deep and wide flexural cracks was observed at the bottom face of the precast slabs, these cracks continued to propagate through the joint at the ultimate load. No interface cracking was observed at the top surface of the slab between the precast slab and the PMMA-PC connection at the ultimate load. After reaching the ultimate load, a series of drops in the force-displacement curve was indicated followed by excessive flexural cracking at the bottom and crushing of the conventional concrete at the top. The test was stopped for safety concerns after reaching approximately 80% of the ultimate load. The ultimate load of this specimen was recorded to be 122.5 kips at 2.63 mid-span vertical displacement. Figure 17 shows an overview of the crack pattern at the bottom face of the test specimen during the test under the ultimate applied load.



**Fig. 17** – Crack pattern, damage, and mode of failure at the top and bottom sides of specimen SP3-T-L-PC.

The overall load versus the mid-span vertical displacement obtained from the middle string potentiometers for the three transverse specimens are presented in Figure 18.



**Fig. 18** – Load-deflection relationship at mid-span of the three transverse specimens.

#### 4.1.4 – Test Results of Specimen “SP4-L-S-UHPC”

The measured peak load of specimen “SP4-L-S-UHPC” was 115.8 kips at 1.51 in mid-span vertical displacement. The overall damage and final status of the SP4-L-S-UHPC specimen after testing is shown in Figure 19.





**Fig. 19** – Crack pattern, damage, and mode of failure at the top and bottom sides of specimen SP4-L-S-UHPC.

#### **4.1.5 – Test Results of Specimen “SP5-L-S-PC”**

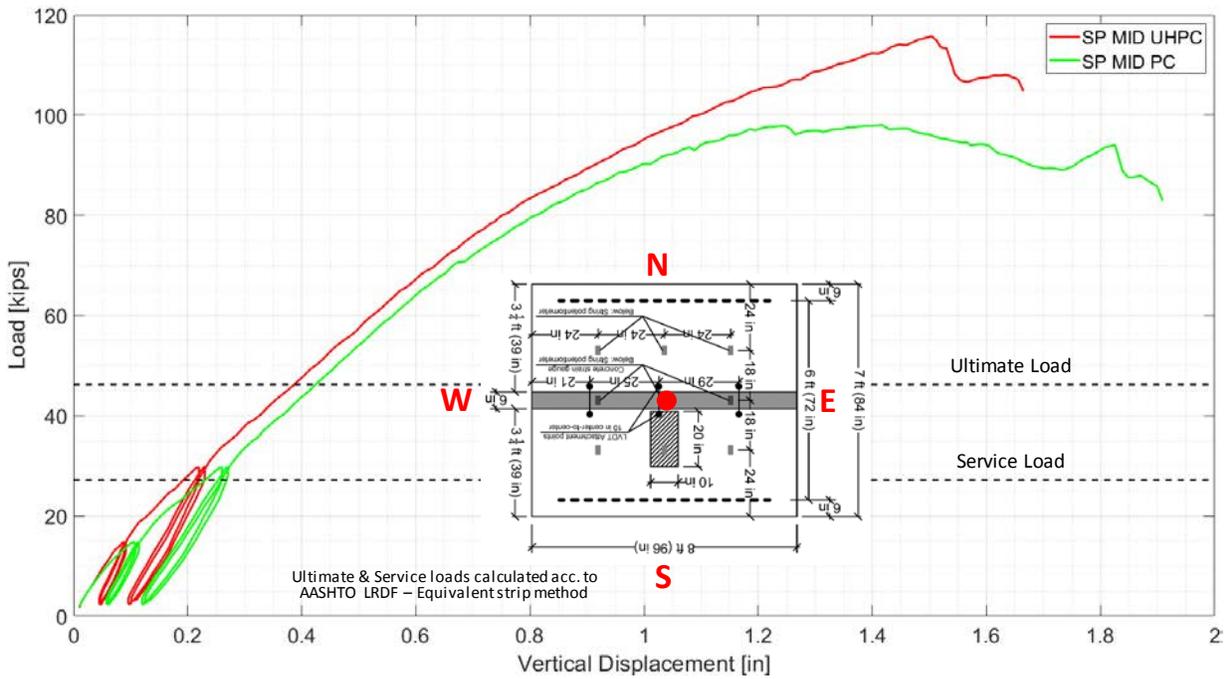
The measured peak load of specimen “SP5-L-S-PC” was 98.2 kips at 1.41 in mid-span vertical displacement. The overall damage and final status of the SP5-L-S-PC specimen after testing is shown in Figure 20.





**Fig. 20** – Crack pattern, damage, and mode of failure at the top and bottom sides of specimen SP5-L-S-PC.

The overall load versus the mid-span vertical displacement obtained from the middle string potentiometers for the two longitudinal specimens are presented in Figure 21.



**Fig. 21** – Load-deflection relationship at mid-span of the two longitudinal specimens.

#### **4.1.6 – Preliminary Conclusions**

- The structural performance of the deck system with PC closure pours used for transverse and longitudinal field connections was found to be comparable in terms of load and deflection capacities to the deck systems with UHPC connections.
- Both UHPC and PC transverse field connections adequately satisfy the service and ultimate load requirements specified in the AASHTO LRFD, where deck systems remain elastic without any major flexural or interface cracking in the joint or any rebar slippage.
- Initial stiffness of the UHPC deck system was found to be higher than that of the PC, which is attributed to the higher mechanical properties of UHPC.
- Both systems showed adequate load distribution capabilities all the way through failure without any shear failure or significant interface debonding. However, the UHPC deck system exhibited two localized main cracks at failure as opposed to several and multiple cracks in the PC deck system at failure.

#### **Task 5 – Summarize the investigation and the results in a draft final report**

Currently, we are working on the final report describing the details of the different tasks done in this project. This report will be submitted to the ABC-UTC steering committee soon for review and comments. Upon addressing the review comments, the report will be finalized and made widely available for dissemination.

### **2.3. ANTICIPATED RESEARCH RESULTS AND DELIVERABLES**

#### **2.3.1. TENTATIVE ABC-UTC GUIDELINE**

One format to disseminate the results from this project is to develop an ABC-UTC guideline for selecting alternative choices to replace UHPC for PBES. The tentative or preliminary guideline can also include design guidelines on how to use such alternative materials for design.

#### **2.3.2. A FIVE-MINUTE VIDEO SUMMARIZING THE PROJECT**

Another format to disseminate the results of this project and contribute to workforce development and outreach is to develop a video and presentation slides to summarize the project. A webinar format can be used to publish and make available such videos or presentations.

#### **2.3.3. FINAL REPORT AND PUBLICATIONS**

As mentioned before in the research plan, a comprehensive report will be developed to summarize all the experimental results. Data sets could also be produced and published using existing or new cyber infrastructure or data platforms if a unified one will be eventually used for ABC-UTC related projects. Publications in peer-reviewed journals and conference presentations will also be considered for delivering project results.

### 3. TIME REQUIREMENTS (GANTT CHART)

To allow for the completion of all the project tasks, the study will be conducted over a period of 18 months (6 quarters) following the schedule in Table 4. The milestones are marked on the schedule, and the following notes explain the deliverables at these milestones.

- a) Mechanical properties of the selected alternative material
- b) The validity of material for deck joints
- c) Final project report.

**Table 4 – Gant schedule of major project tasks and milestones**

Tasks	Year 1				Year 2	
	Q1	Q2	Q3	Q4	Q1	Q2
1. Literature search	X					
2. Mechanical characterization		X <sup>a</sup>				
3. Experiments and specimens design		X	X			
4. Deck panels joint tests			X	X	X <sup>b</sup>	
6. Final report and dissemination						X <sup>c</sup>

	Completed or work in progress		Remaining
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The percentage of completion of this project is as follow:

Item	% Completed
Percentage of Completion of this project to Date	90